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Plasma-Sprayed Coatings for Lubrication of a Titanium Alloy in Air at 430° C

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SUMMARY

Titanium and many of its alloys are known to be difficult to lubricate. During sliding, they have a strong tendency to give high and erratic friction accompanied by severe adhesive wear and galling. Self-lubricating plasma-sprayed coatings were investigated, therefore, as a possible approach to obtaining low friction and wear during sliding contact with a titanium alloy. Titanium-5 Al-2.5 Sn alloy pins were slid against plasma-sprayed coatings of pure silver and of three composite formulations at a temperature of 430° C and a sliding velocity of 13 centimeters per second in air.

Plasma-sprayed, pure silver coatings were effective in providing low pin wear. However, silver coatings greater than 0.025 millimeter in thickness underwent severe plastic deformation and gross transfer to the sliding surface of the pin. Coatings with a one-to-one weight ratio of silver and nichrome were harder and did not deform so severely, but friction and pin wear increased. The addition of calcium fluoride was beneficial in reducing wear. A coating containing a further addition of a specially formulated glass was even more effective in providing low wear and a stable friction coefficient of about 0.2 over a long duration (20 hr) of sliding. This four-component coating was designated PS101. It has the following nominal composition by weight: 30 percent silver-30 percent nichrome-25 percent calcium fluoride-15 percent glass.

INTRODUCTION

Titanium alloys have high strength and creep resistance up to about 480° C (900° F). This consideration combined with the excellent strength to weight ratio and corrosion resistance of titanium alloys make them suitable for use in aircraft applications, especially in those jet engine components, where temperatures are too high for aluminum alloys but do not exceed 480° C (900° F).

Unfortunately, when sliding contact occurs, most titanium alloys are unsuitable because of their very poor friction and wear characteristics (refs. 1 to 3). Exceptions to this are titanium alloys with a high percentage (10 to 20 percent) of tin. For example, a titanium alloy containing 20 percent tin was shown in reference 4 to be wear resistant and nongalling when in sliding contact with titanium-6 percent aluminum-4 percent vanadium (Ti-6 Al-4 V).

Another approach to obtaining improved friction and wear for titanium alloys in sliding contact is to coat one or both surfaces. Chemical conversion coatings (ref. 5) and hard coats (ref. 6) have been evaluated for this purpose. Some of them reduce wear but generally do not provide low friction coefficients. Also thin, hard coats tend to crack and spall when the substrate deforms elastically under high surface stresses.

Thin (0.02-mm) fused coatings of stable fluorides with silver additions have provided lubrication for nickel-base super alloys during repeated thermal cycles from room temperature to 760° C (1400° F)(ref. 7). Unfortunately the coating application procedure requires a high temperature heat treatment which would not be suitable for titanium. However, coatings containing stable fluorides and silver can also be applied by the plasma-spray process with minimal heating of the substrate material. A plasma-sprayed composite coating containing silver, nichrome, calcium fluoride, and glass (NASA Lube PS101) is an example of an oxidation resistant coating which has lubricated nickel-base alloys over a wide temperature spectrum from cryogenic conditions to 870° C (1600° F)(ref. 8). Therefore in the present program, it was decided to study the effectiveness of PS101 and other silver-containing, plasma-sprayed coatings for the lubrication of titanium alloy.

A specimen temperature of 430° C (800° F) was chosen as a representative extreme temperature for a titanium alloy sliding contact application. Load in all cases was 250 grams on a hemispherically tipped (4.8-mm rod) titanium alloy pin in sliding contact with the coatings at a velocity of 13 centimeters per second.

MATERIALS AND COATING PROCEDURES

The description of the plasma-spray powders and the coating compositions are given in tables I and II. The coating compositions were increased in complexity from a one-component (pure silver) to a four-component system. All compositions, except the pure silver, contained a one-to-one weight ratio of silver and nichrome (1:1 Ag-NiCr). Calcium fluoride (CaF_2) was the added material in the three-component coatings, and a sodium-free glass was the fourth component. The purpose of the nichrome was to provide a harder, and therefore less deformable, coating material than pure silver. Calcium fluoride addition was explored because of this compound's known high temperature lubricating ability (ref. 9). Glass can be expected to provide glazing tendency on the sliding surface as well as providing a degree of oxidation-protection to the nichrome component (ref. 10).

Typical plasma-spray parameters for all four silver-containing coatings when using an SG-1 type of spray gun were the following: Arc and powder carrier gun was

argon flowing at 1.3 cubic meters per hour and 0.4 cubic meter per hour, respectively. Arc current was 350 amperes at 24 volts. Target distance was 10 to 12 centimeters.

Coatings were initially applied to a titanium-6 aluminum-4 vanadium (Ti-6 Al-4 V) alloy. The substrate was sand blasted, then plasma sprayed with a nichrome bond coat before application of the lubricating, plasma-sprayed coating. The bond coat was typically 0.07-millimeter thick. An excess thickness of lubricant coating was applied, then hand lapped on graded, wet abrasive paper to a final lubricant coating thickness of 0.17 millimeter (except where otherwise specified). Final lapping was on 600 grit polishing paper. This procedure resulted in good coating adhesion on Ti-6 Al-4 V alloy.

After the ability to achieve adequate coating adhesion on Ti-6 Al-4 V had been demonstrated, the subsequent coatings were applied to a more readily available nickel-base alloy (Inconel 750) for friction and wear tests. (Under conditions of adequate coating adhesion, the composition of the substrate alloy would not be likely to influence the friction and wear characteristics of these relatively thick coatings). The pin material in sliding contact with the coatings was titanium-5 aluminum-2.5 tin (Ti-5 Al-2.5 Sn) in all experiments.

APPARATUS AND TEST PROCEDURE

The apparatus used is shown in figure 1. The basic elements were a rotating disk (diameter, 6.35 cm) and a hemispherically tipped pin specimen (diameter, 0.95 cm) in sliding contact. The pin specimen was loaded against the rotating disk by a deadweight system; the force was transmitted through a shaft vertically mounted in a porous-metal gas-lubricated bushing. The atmosphere was dry air, introduced at the bottom of the chamber as well as through the gas bearings.

The friction force was sensed by a temperature-compensated strain gage bridge mounted on a dynamometer ring and was continuously traced on a strip-chart recorder. Rotational speed was measured by a magnetic pickup connected to an event counter. Specimen temperature was controlled automatically using the signal from an infrared pyrometer, which was sighted through a hole in the chamber wall onto the pin specimen just above the pin-disk contact area.

The specimens were solvent cleaned with ethyl alcohol. They were then rinsed, in distilled water, and dried just before use.

Specimens were mounted in the test chamber, which was then closed and purged with dried air (<100 ppm H_2O). The disk was rotated and heated until the specimen temperature stabilized at 430° C. The rider was then loaded against the rotating disk.

After a test, pin wear volume was calculated from the diameter of the circular scar. Coating wear was obtained from radial profilometer traces across the wear track. The cross-sectional wear area was averaged from three or four profiles then multiplied by the average circumference of the track to give the coating wear volume. Wear volume was divided by the total sliding distance and the load to give the following wear coefficient:

$$K = \frac{\text{cm}^3 \text{ (wear)}}{\text{cm (sliding distance)} \times \text{kg (load)}}$$

RESULTS AND DISCUSSION

Effect of Coating Composition

The friction characteristics of the coatings over test durations of up to 20 hours are shown in figure 2. Surface profiles of the wear tracks at the completion of the tests are shown in figure 3. Pin and coating wear rates are given in figure 4. Pin wear rates (ref. 4) against the uncoated Ti-6 Al-4 V and against a titanium diboride hard coat on this alloy are also given for comparison.

The lowest sliding friction early in the tests was observed with pure silver. Friction coefficients were less than 0.1 for 5 hours then increased abruptly. No wear occurred on the hemispherical pin, but silver immediately transferred to it and the sliding combination was essentially silver on silver. Surface profilometry (fig. 3(a)) showed that the coating was very severely plastically deformed, but the pin had not penetrated through the silver to the substrate. This excessive plastic deformation and the heavy silver transfer make these relatively thick silver coatings unacceptable for the type of sliding contact employed in these tests. The effect of coating thickness will be described later.

The addition of nichrome produced coatings with a low initial friction coefficient of 0.1; however, the friction coefficient gradually and continuously increased during the test to 0.33 after 9 hours. The coating wear track profile (fig. 3(b)) shows considerable coating wear but much less indication of gross plastic deformation than pure silver. Also, the heavy transfer, which is characteristic of pure silver, did not occur. Pin and coating wear rates are given in figure 4.

Calcium fluoride addition (coating PS106) resulted in significant reductions in pin and coating wear rates. Initial friction coefficients were higher than with silver and one-to-one silver-nichrome, but were very steady and constant at a value of 0.2 for the entire 9-hour test duration.

The four-component coating (PS101) had about the same friction coefficient as PS106 (0.2). A small increase in pin wear rate occurred compared to that observed with PS106, but the coating wear rate was so low that the test was continued for a duration of 20 hours with very little penetration of the coating (fig. 3(d)).

These results indicate that plasma-sprayed silver is very effective as a dry lubricant coating but must be combined with other components to reduce plastic deformation and excessive silver transfer to the counterface material. Calcium fluoride did not reduce the friction coefficient for short test durations, but resulted in a coating with a very stable, moderate friction coefficient of about 0.2 over a long duration of sliding. It also had a beneficial effect in reducing pin and coating wear. The glass addition caused a small increase in pin wear but a substantial reduction in coating wear.

The wear data from reference 4, which is included in figure 4 of this report shows that wear rates of Ti-5 Al-2.5 Sn pins were lower against any of the plasma-sprayed coatings than they were against a titanium diboride (TiB_2) hard coat or against uncoated Ti-6Al-4V.

Effect of Thickness of Silver Coatings

The main problems with the relatively thick (0.17 mm) silver coatings were severe plastic deformation of the silver and heavy adhesive transfer of silver to the titanium alloy pin, therefore, thinner silver coatings were also evaluated. It was expected that plastic deformation would necessarily be reduced for the thinner coatings for which the harder substrate would provide a more effective support.

The effects of silver coating thickness on friction and wear are shown in figures 5 to 7. The friction coefficients for 0.07 millimeter coating was about 0.1 or nearly the same as that of the 0.17 millimeter coating during the first 5 hours but remained at this low value for the total duration of 7 hours while the friction of the thicker coating took a sharp upturn after 5 hours. Surface profiles of the wear tracks on the coating (fig. 6(b)) showed much reduced plastic deformation of the silver. The depth of the track was about 0.03 millimeter or about one half the coating thickness; therefore, no contact occurred between the titanium alloy pin and the coating substrate. Silver transfer to the pin was reduced and some pin wear occurred (fig. 7).

Finally, a 0.02-millimeter coating was evaluated. Friction coefficients were about 50 percent higher (0.15) than in the case of the thicker coatings, but remained constant for 8 hours except for a time about one half way through the test when sliding was a little rough and the friction coefficient briefly peaked at 0.2. This was probably caused by a temporary penetration of the coating over a small area of the

wear track which subsequently "healed" by plastic flow of silver over the failed area and the pick up of additional silver from the sides of the wear track as wear of the hemispherically tipped pin progressed.

The wear data of figure 7 and the surface profiles of figure 6(c) show that both pin wear and coating wear rates were very low. The silver flowed readily under the shear stress of the sliding contact. Figure 6(d) shows that, in some of the tests, the silver was displaced and redeposited in other areas as particles or patches which were up to 0.03 millimeter thick. This flow characteristic can be advantageous as previously described for "healing" small areas where the coating is worn away. However, redistribution of the silver can also be a problem if it results in undesirable changes in bearing clearances.

In general, the aforementioned results indicate that plasma-sprayed silver coatings, lapped to a thickness of about 0.02 millimeter, may be adequate for lubricating to 430° C. No peeling or other indications of bond failure that sometimes occur with electroplated silver at elevated temperatures were observed with the plasma-sprayed coatings investigated in this study.

SUMMARY OF RESULTS

Self-lubricating plasma-sprayed coatings were tested to obtain low friction and wear during sliding contact with a titanium alloy. The following results were obtained:

1. Plasma-sprayed coatings containing silver were effective solid lubricants in sliding contact with a titanium alloy (Ta-5Al-2.5 Sn) in air at 430° C.

2. Among the thick coatings (0.17 mm), the best results were obtained with a coating composed of 30Ag-30NiCr-25CaF_2-15 glass (PS101). Low pin wear and extremely low coating wear occurred. The wear surfaces were smooth and the friction coefficient was very steady at 0.2.

3. Very low friction (0.05 to 0.15) was obtained with pure silver coatings of 0.02 to 0.17 millimeter thickness. However, excessive plastic deformation of the coatings occurred in all but the 0.02-millimeter-thick silver coating.

Lewis Research Center,
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Cleveland, Ohio, May 4, 1979,
506-16.

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TABLE I. - POWDERS

Powder material	Range of particle sizes, micrometers	Source
Silver (Ag)	50 to 150	Commercial, plasma spray powder
Nichrome (NiCr) 80 Ni-20 Cr	50 to 150	Commercial, plasma spray powder
Calcium fluoride (CaF_2)	5 to 20	Reagent grade chemical
Glass (58 SiO_2-21.2 BaO 7.8 CaO-13.0 K_2O)	50 to 150	Laboratory preparation from reagent grade chemicals

TABLE II. - COATINGS

Identification number	Composition, wt. percent
PS109	100 Ag
PS108	50 Ag-50 NiCr
PS106	35 Ag-35 NiCr-30 CaF_2
PS101	30 Ag-30 NiCr-25 CaF_2-15 glass

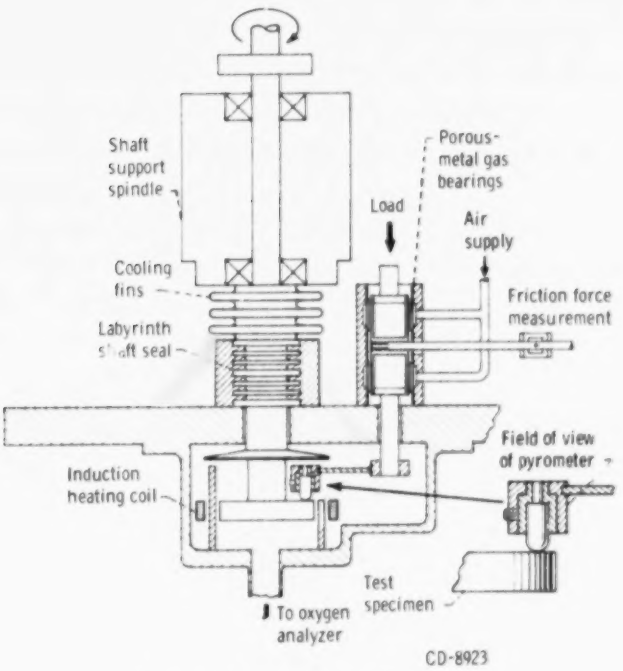


Figure 1. - Friction and wear test apparatus.

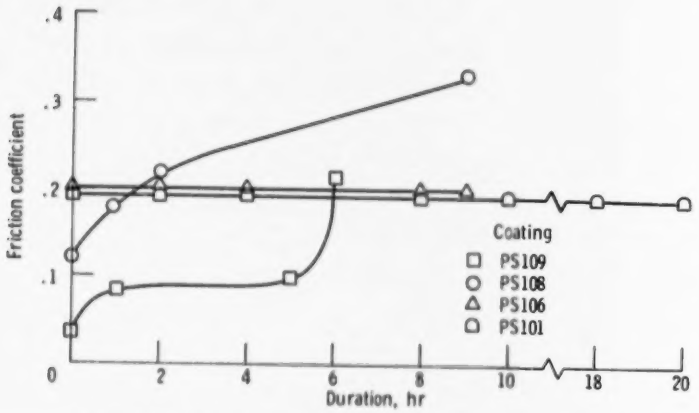
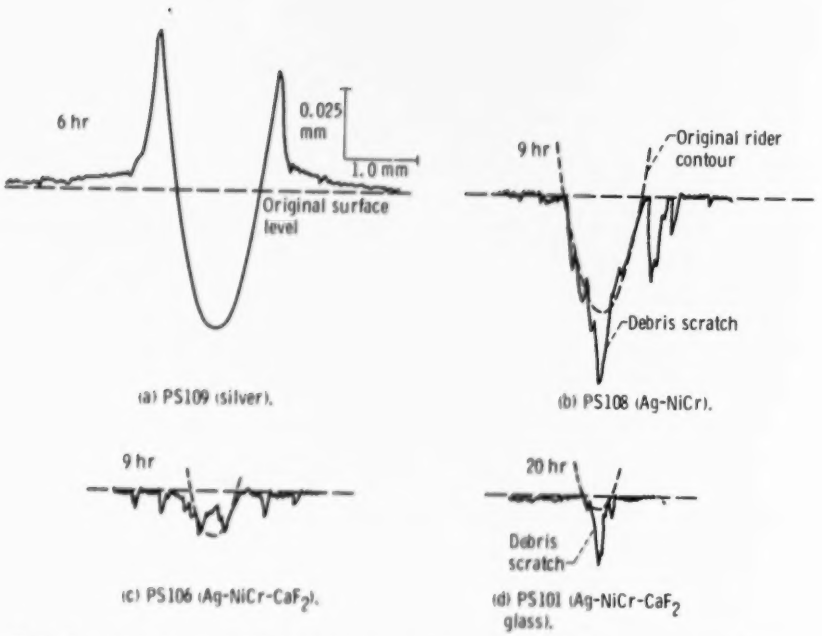


Figure 2. - Friction characteristics in air of 0.17-millimeter-thick plasma-sprayed composite coatings containing silver. Ti-5 Al-2.5 Sn pin material; 430° C; 250-gram load; 13-centimeter-per-second sliding velocity at 50 rpm.



(a) PS109 (silver).

(b) PS108 (Ag-NiCr).

(c) PS106 (Ag-NiCr-CaF_2).

(d) PS101 (Ag-NiCr-CaF_2 glass).

Figure 3. - Wear track cross sections showing wear and deformation of 0.17-millimeter-thick plasma-sprayed composite coatings containing silver. Ti-5 Al-2.5 Sn pin material; 430° C; 250-gram load; 13-centimeter-per-second sliding velocity at 50 rpm.

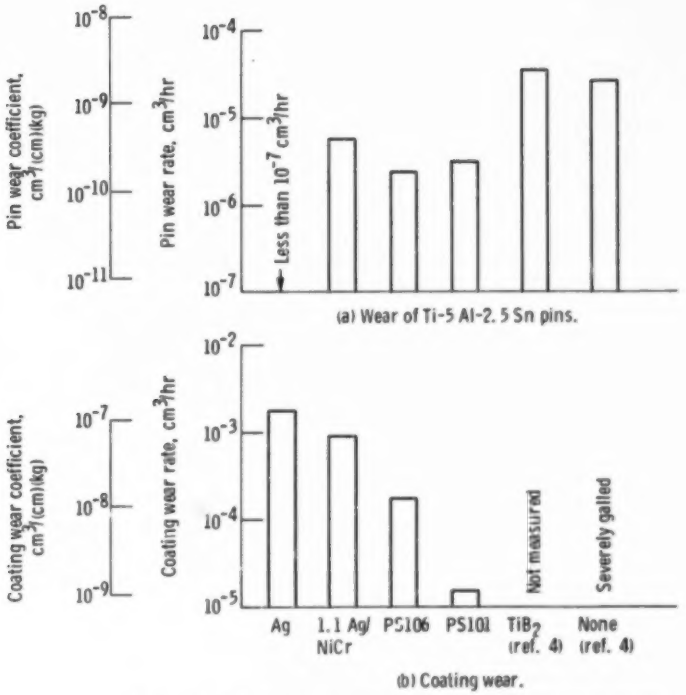


Figure 4. - Effect of coating composition on pin and coating wear in air. 0.17-Millimeter-thick coatings on disks; 4.8-millimeter-radius hemispherically tipped pins; 430° C; 250-gram load; 13-centimeter-per-second sliding velocity at 50 rpm.

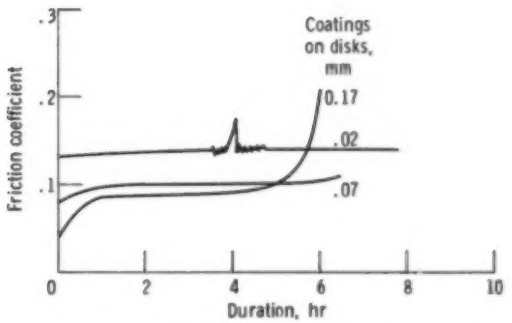
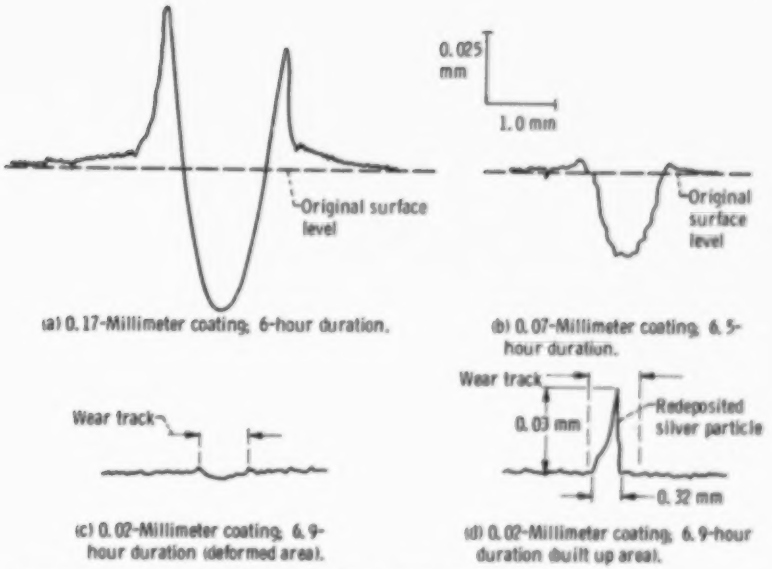


Figure 5. - Effect of coating thickness on friction of plasma-sprayed silver in air. Ti-5 Al-2.5 Sn pin material; 430° C; 250-gram load; 13-centimeter-per-second sliding velocity at 50 rpm.



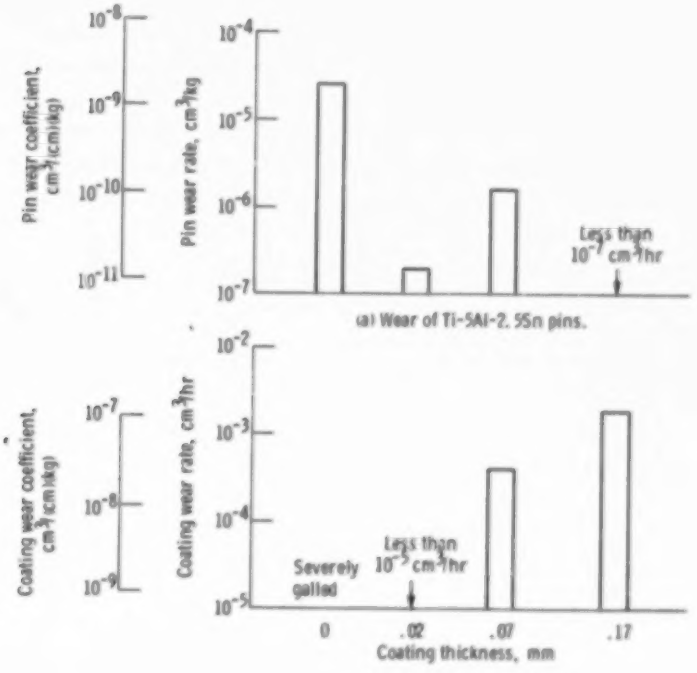
(a) 0.17-Millimeter coating; 6-hour duration.

(b) 0.07-Millimeter coating; 6.5-hour duration.

(c) 0.02-Millimeter coating; 6.9-hour duration (deformed area).

(d) 0.02-Millimeter coating; 6.9-hour duration (built up area).

Figure 6. - Wear track cross sections showing effect of coating thickness on wear and deformation of plasma-sprayed silver coatings. Ti-5 Al-2.5 Sn pin material; 430° C; 250-gram load; 13-centimeter-per-second sliding velocity at 50 rpm.



(a) Wear of Ti-5Al-2.5Sn pins.

(b) Wear of the silver coating.

Figure 7. - Effect of silver coating thickness on pin and coating wear in air. Silver-coated disks; 48-millimeter-radius hemispherically tipped pins; 430° C; 250-gram load; 13-centimeter-per-second sliding velocity at 50 rpm.

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15. Supplementary Notes

16. Abstract

Plasma-sprayed coatings of pure silver and of composite materials containing silver were investigated as possible self-lubricating coatings for titanium alloys in air at 430° C. Pure silver provided low friction but was prone to severe plastic deformation and excessive transfer except in coating thicknesses of 0.02 mm or less. Additions of nichrome, calcium fluoride, and glass to silver were all beneficial in reducing plastic deformation and otherwise improving the coatings. The longest coating wear life, low wear of Ti alloy pins in sliding contact with the coatings, and a steady friction coefficient of 0.19 were obtained with a four-component coating of 0.17 mm thickness. The coating composition, in weight percent is 30 nichrome-30 Ag-25 CaF_2-15 glass.

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